CLOUD PATTERNS

PART 1: SOME ASPECTS OF THE ORGANIZATION OF CLOUD PATTERNS

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[Manuscript received July 3, 1963; revised September 4, 1963]

ABSTRACT

The organization of convective clouds into streets and bands as observed in cloud study field trips, in plots of radar echoes, and in pictures taken by TIROS satellites and high-flying aircraft is described, and some of the physical factors affecting the cloud patterns are discussed. The need for more observational data and for better understanding of atmospheric energetics and dynamics in order to forecast cloud patterns is emphasized.

In a memorial to Harry Wexler it is appropriate to include a discussion of the patterns formed by convective cloud cells because although Wexler wrote a number of papers on the organization of the large-scale circulation of the atmosphere, he was also concerned with whether individual convection cells are randomly spaced or whether they, too, are organized into patterns. It was his conviction that they must be organized, as a result of the interaction of physical processes and the terrain; and if they are organized, it seems reasonable that they should be predictable, once the physical basis of the patterns is discovered. Moreover, organized clouds should indicate the presence of mesoscale horizontal atmospheric eddies. Wexler was interested in determining how such eddies add or subtract meteorological properties (such as angular momentum or kinetic energy) to the general circulation [15]. Two of us among the many who leaned heavily on Wexler's advice and enthusiastic encouragement would like to present here as a tribute to him the results of our examination of cloud patterns which we undertook during the summer of 1961 at his suggestion.

During the summer of 1961 we spent most of two months with Dr. H. Riehl at Colorado State University in Fort Collins, Colo., with trips throughout Colorado and the adjoining States. At that time there was a stationary ridge aloft over the Rockies with southerly surface winds over the eastern ranges and over the High Plains. Aloft the winds over the area were generally northwest. We were fortunate that for the first month and one-half the weather regime was such that at Fort Collins we had daily rain or hail showers. Later the rain occurred somewhat farther north. But the setup was extraordinarily good for observing how cloud patterns develop over the mountains and move out over the Plains.

Our impression of the daily convective clouds near Fort Collins was "utter choas before seven, organized before eleven." However, at dawn when it was usually clear except for a few stationary lenticular altocumulus clouds near the higher peaks, we had our first clue as to the future organization of the daytime thunderstorms. The lenticular clouds were formed where there were updrafts in the standing waves produced by winds blowing over the mountains. It seems reasonable to suppose that when, later on in the day, convective clouds moved into these areas of forced updraft their development was enhanced. This did appear to occur. Shortly after sunrise small isolated cumuli appeared all along the eastern front of the mountain area. Soon cumuli of various sizes and shapes covered most of the peaks of the Front Range and the foothills. As the morning wore on, towering cumuli and cumulonimbi developed considerably to the west of the Front Range. By midday on nearly all the days we were there, a few of the mountain thunderstorms produced anvils which spread rapidly downwind (toward the southeast). By early afternoon several long anvils could be seen extending from horizon to horizon. Generally they appeared to emanate from those portions of the mountains where the early-morning lenticular clouds had been seen. This suggests that stationary mountain waves play a part in organizing convective cloud patterns.

By late afternoon mountain thunderstorms had started moving eastward from the mountain front over the plains. Here a remarkable change set in. Tremendous downdrafts were generated when the rain and hail fell through the deep layer of hot, dry air over the plains. Blocked by the escarpment to the west, the downdraft became a blast of cold air rushing eastward. The western sides of the thunderstorms were dissipated by subsidence feeding the downdraft; heavy rain and hail falling from the extreme western (rear) edges of the clouds were followed by dramat-

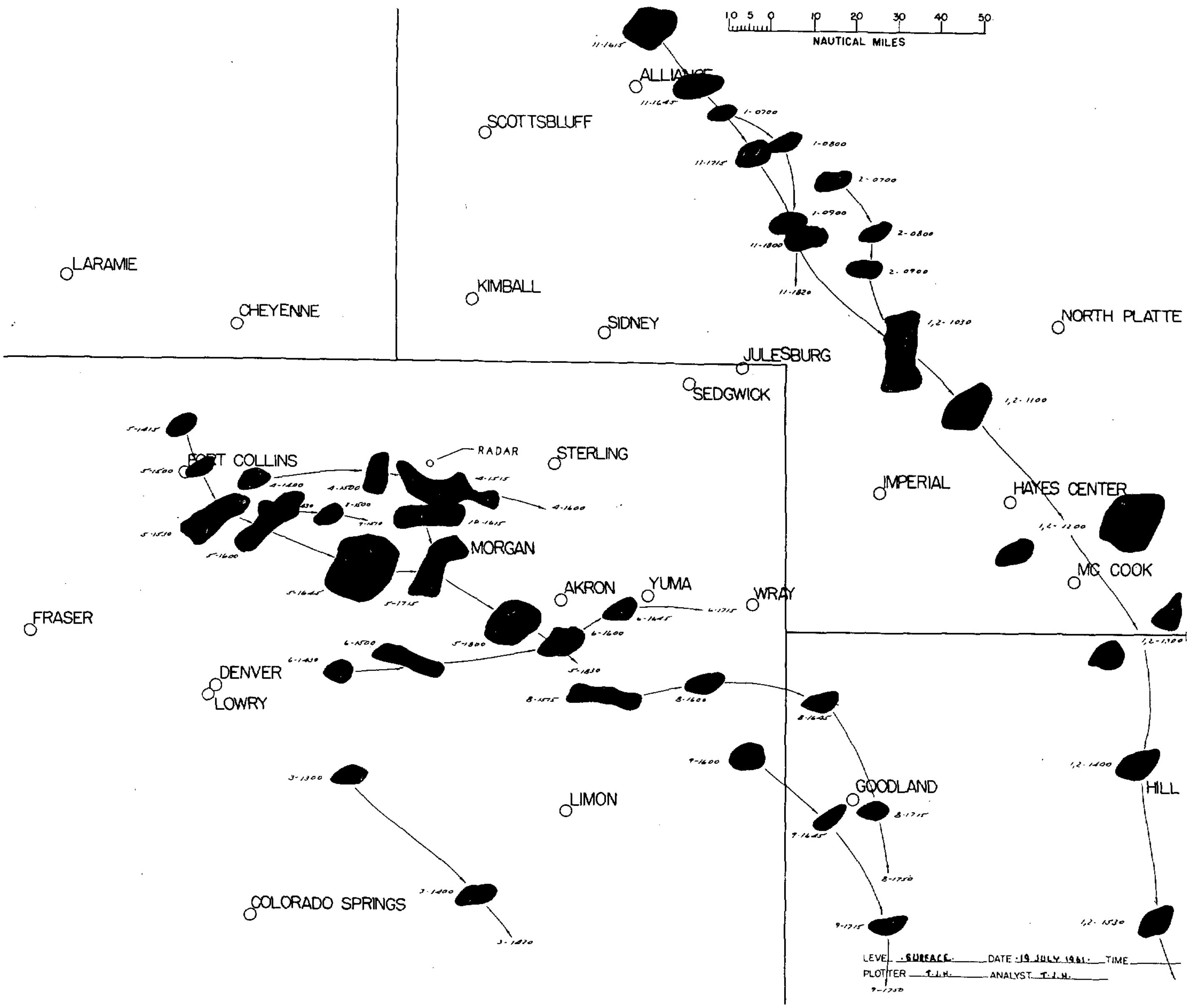

FIGURE 1.—Radar echoes at approximately one-hour intervals for July 19, 1961. Note the two principal paths with no echoes in between. (From Schleusener and Henderson [7].)

ically clear skies. Meanwhile the rows of thunderstorms moved eastward, increasing in size and remaining visible on the eastern horizon far into the night. Perhaps these storms are the forerunners of the nighttime thunderstorms so frequent in the Midwest.

As the thunderstorms moved across the plains, their heavy rain and hail fell in very long, narrow swaths parallel to, and frequently along, the areas covered earlier by the elongated anvils. On several occasions as the individual thunderstorms moved southeastward, they merged into long bands of clouds parallel to the mountains and propagated rapidly eastward as newly formed squall lines. Typically, each line was composed of numerous thunderstorm cells, separated by as much as 10 to 50 mi., even though the cloud pattern was continuous. Whenever possible, we drove eastward to examine such lines of storms as they moved away from the mountains. The lines of thunderstorms seemed to move away from the mountains too fast to be wind-driven. The excessive motion appeared to be due to growth on the forward side and decay on the rear. Another thing we noticed while following individual cells by auto was that they seemed to grow to the right of the path the cloud was following and dissipate to the left.

The organization of these lines of showers was synoptically more evident in the cloud distribution than in the rain cells shown by radar. The organization of the rain cells became apparent in time sequences. (For example,

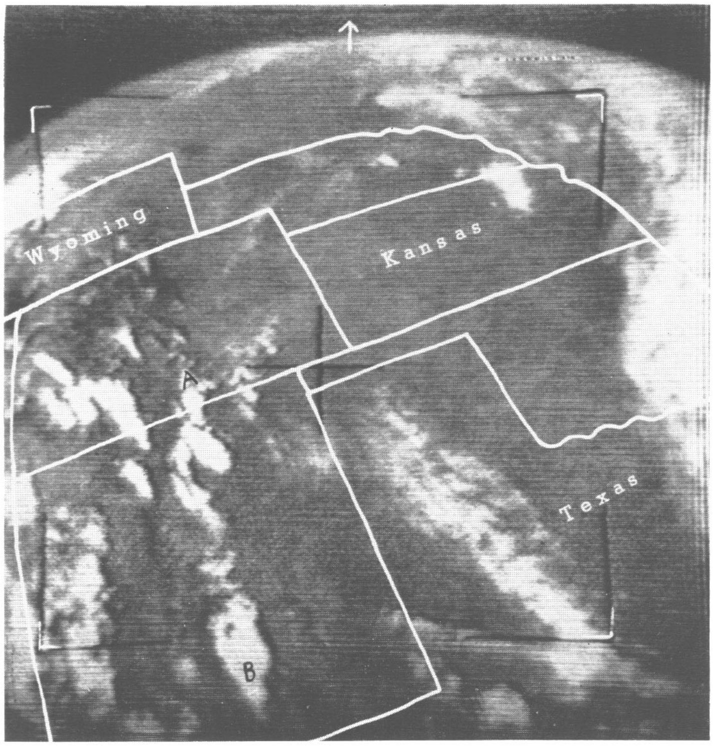

Figure 2.—TIROS III picture, August 23, 1961, 2052 GMT. Newly formed thunderstorms over the Front Range with north-south line A–B beginning to develop.

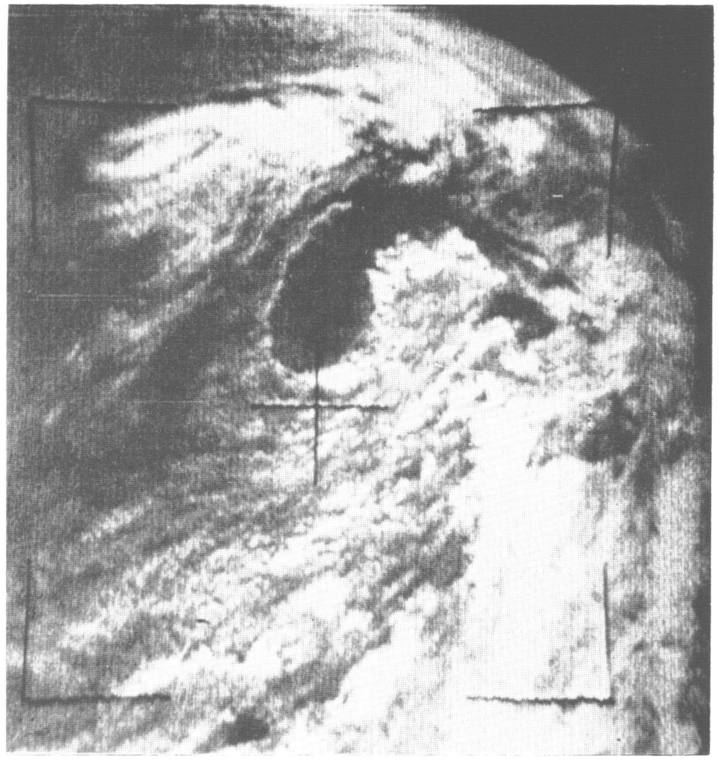

Figure 3.—TIROS III picture about 2100 GMT, August 25, 1961, showing Lake Michigan and vicinity.

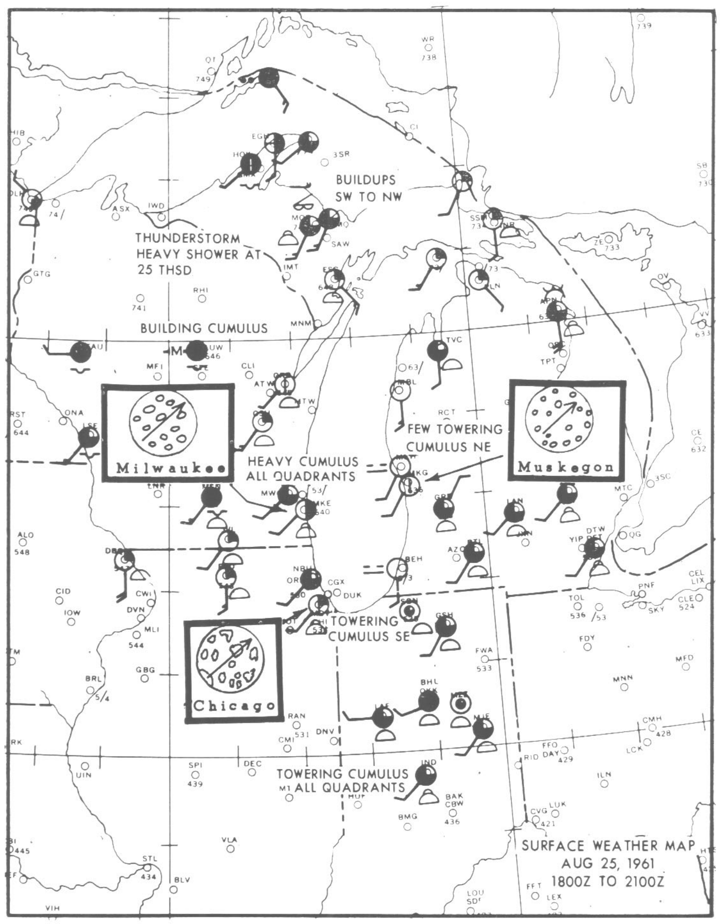

Figure 4.—Surface weather data for 1800–2100 GMT, August 25, 1961, including detailed cloud distribution as seen from the ground.

fig. 1.) Although the cloud bands usually developed parallel to the mountains, the local radar and ground photography program conducted by Riehl, Schleusener, and Henderson of Colorado State University [6, 7] showed that the rain moved in paths nearly perpendicular to the mountains, roughly parallel to the high-level winds. The long narrow paths of truly remarkable magnitude (fig. 1) covered by showers and thunderstorms were clear evidence of an organization of the flow pattern which, like the organization of the clouds, was too small to be recognized from our synoptic network of data but too large to be recognized by eye at any one place. The organization of the patterns into long, narrow paths parallel to the 50-mb. flow *was* noticeable from the radar tracks of the path of precipitation cells. But the organization of clouds into lines roughly parallel to the mountains and perpendicular to the upper winds (the squall line) was rarely noted by the radar in this area.

This is the sort of thing that satellite pictures show up well (fig. 2). The combination of satellite pictures, showing the cloud distribution, and radar pictures, showing movement and spacing of showers, should make possible a systematic detection of organized convective patterns.

The problem right now is that our observational network is inadequate, both with regard to scale and to type of observation. We encountered this problem in Colorado, but as Wexler [11] pointed out, it is worldwide. Even in

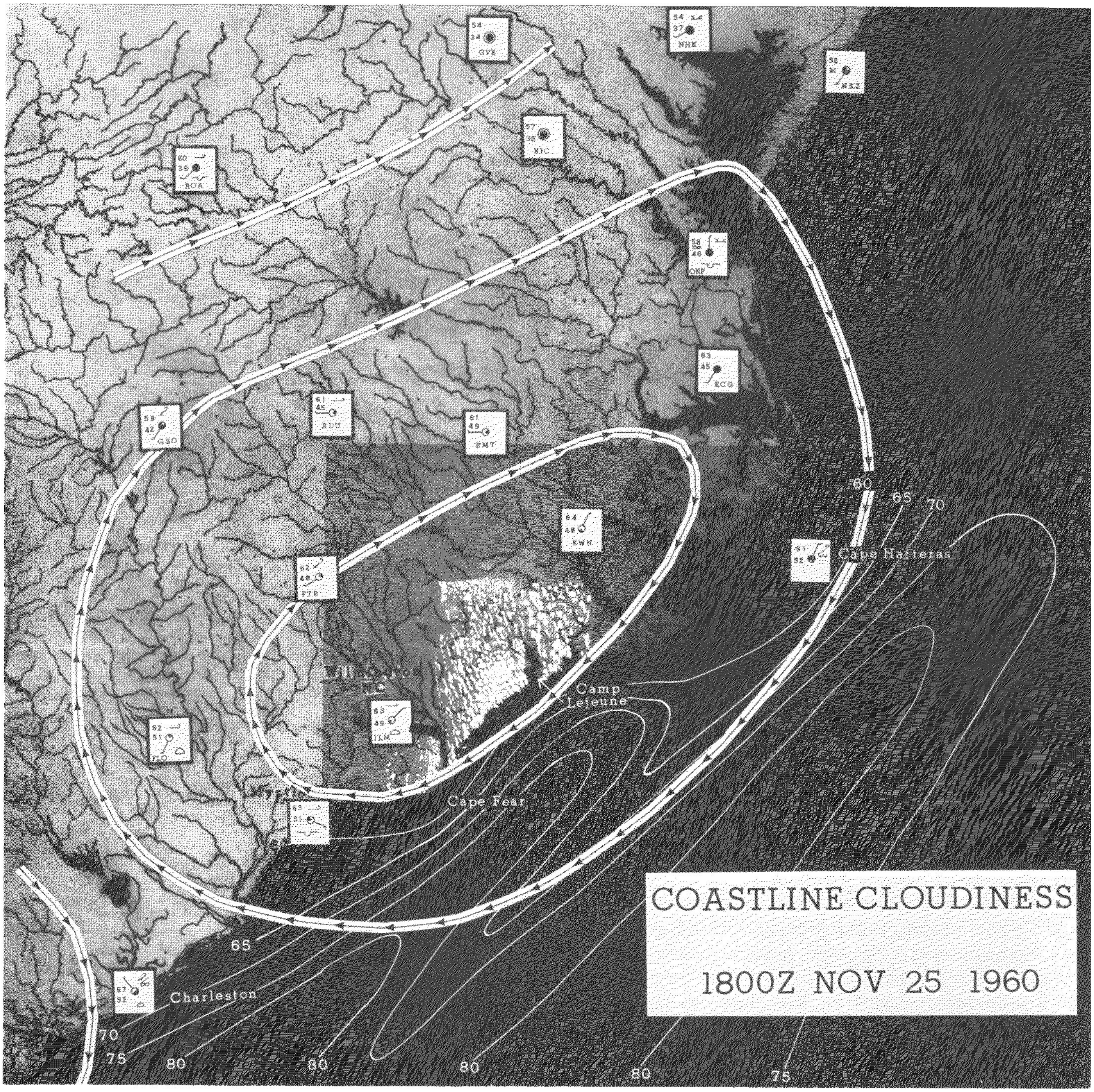

FIGURE 5.—Diagram of North Carolina coast near Wilmington with surface flow pattern, sea surface isotherms, and a schematic representation of clouds as seen from TIROS satellite (narrow-angle camera), afternoon, November 25, 1960. Note cloud streets ending abruptly at the water's edge.

populous areas where our observation network is relatively dense, weather patterns as large as Lake Michigan (70 mi. wide, 350 mi. long) can exist undetected. For example, take the situation in the vicinity of Lake Michigan during the afternoon of August 25, 1961.

The flow aloft was southwesterly. Figure 3 is the satellite picture of this area. Lake Michigan shows up as a clear black area with a heavy cover of clouds on its eastern shore and a sharp white outline along its western shore. Figure 4 shows the surface reports including the Coast Guard stations, as well as the whole-sky reports, for the afternoon between 1800 and 2100 GMT. With all these data one could not deduce that it was clear over Lake Michigan with a narrow row of clouds over the western shore and with a heavy cloud cover to the east.

Turning to the question of the possible organization of smaller cumulus clouds, we made use of pictures made with cameras of high resolution (such as the narrow-angle cameras mounted on TIROS I and II satellites and the cameras on the Mercury shots). For example, figures 5 and 6 show fair-weather cumulus patterns over the North Carolina coast. In contrast to our example over Lake Michigan where the significant cloud patterns could be measured in hundreds of miles, figures 5 and 6 show patterns of individual cells down to the order of ⅕ to ½ mi. in diameter.

Figure 5 is a diagram of the North Carolina coastal plain near Cape Hatteras for the afternoon of November 25, 1960, with the available surface reports, the surface wind circulation, and the rivers and bays on it. The white lines on the black Atlantic Ocean are sea surface isotherms based on 25 ships in this area. Near the center of the picture (near Camp Lejuene) is a diagram of the narrow-angle camera satellite picture of the area, shown in figure 6. The most striking feature of the picture is the abrupt end of the neat rows of fair-weather cumuli at the coast and at the edge of the broad lagoon at Camp Lejeune. Other satellite pictures showed that, except for the clear strip along the shore, the Atlantic was covered fairly extensively with clouds. But from our surface observations (fig. 5) we find no evidence of either the cloud streets over the land or their abrupt termination at the coast.

Another instance of well-defined fair-weather cumulus patterns too small to be detected by our regular observing network is that shown by the Mercury shot over southern Florida, January 31, 1961 (fig. 7). The sky is clear over Lake Okeechobee, and the small cumulus cells are lined up, as in the previous example, in rows. However, the rows here continue out over the sea eastward across the Atlantic coastline. In the left central part of the picture the white patches (cumulus clouds) tend to merge together, showing an intensification of cumulus activity there.

Figures 8, 9, and 10 show pictures of southern Florida taken from an airplane flying at about 27,000 ft. Figure 8 shows Lake Okeechobee with its ring of cumulus clouds in more detail. Notice how the clouds hug the shoreline on one side of the lake and are at a distance back from it on the other shore. Figure 9 shows the coast of Florida (with Lake Okeechobee in the upper right). The picture shows clear skies over the coast and for a short distance offshore. The rows of cumuli are more developed close to the coast than they are farther inland. Figure 10 is similar except that it shows the cumuli out over the ocean, separated from the clouds over the land by a clear strip. This seems to be a typical setup during the sea breeze regime, with the clear area located where the air sinks over the water. The large clouds just inland mark the convergence of the sea breeze with the heated air inland. Again, the point is

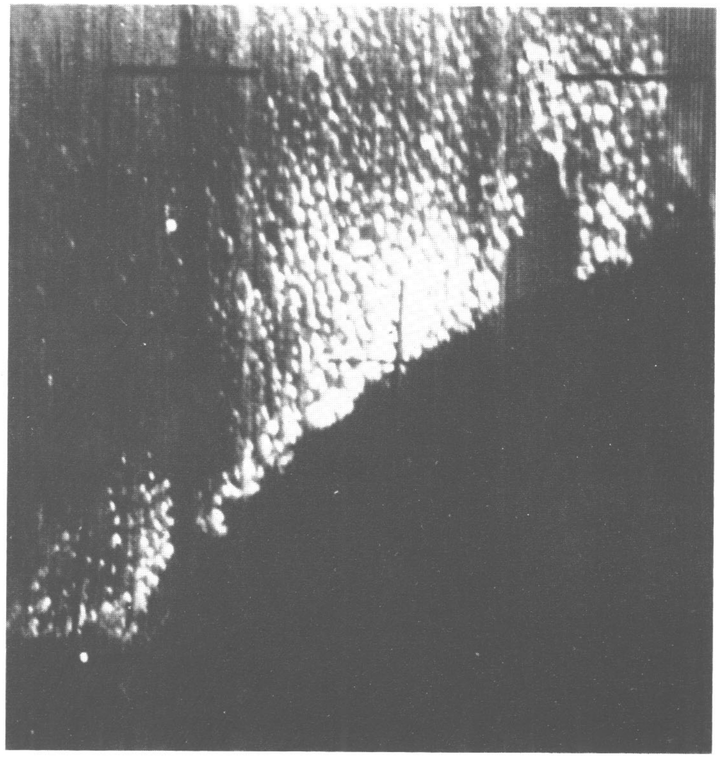

FIGURE 6.—TIROS II narrow-angle picture of clouds along North Carolina coast near Wilmington as sketched in figure 5.

that high-altitude pictures show organized cloud patterns which are missed by our usual weather reports.

Given sure evidence of the organization of convective clouds, the next thing the meteorologist wants to do is forecast these cloud patterns, and the forecasting hinges on the discovery of the physical basis of the cloud organization. The subject has been treated by Wexler [13, 14], Simpson [9], Riehl and Malkus [5], Atlas [1], Hubert [3], Kuettner [4], Gentry [2], Riehl and Schleusener [6], and Schuetz and Fritz [8]. A new and to us a very exciting hypothesis for the organization of clouds into parallel bands has recently been proposed by Freeman. His explanation is contained in the second part of this paper. If this hypothesis turns out to be true, and we find to which scale of bands it is most applicable, our understanding of banding will certainly be enhanced. His hypothesis would be equally applicable over land and over water; however, each factor in his equations is affected by the underlying surface.

The importance of the underlying surface in determining the cloud pattern is clearly illustrated by the high-level pictures of the Lake Michigan area, of the Carolinas, and of southern Florida, and it becomes clear that water bodies play a decisive role in determining the distribution of clouds near them. In each case there existed water-land contrasts under an upper anticyclone, physically similar to the area and synoptic situation discussed years ago by Wexler [10, 12]. Observations were scant then, but Wexler pointed out that important weather patterns in the Great Lakes area are produced by a combination of differential heating with differential friction. It seems

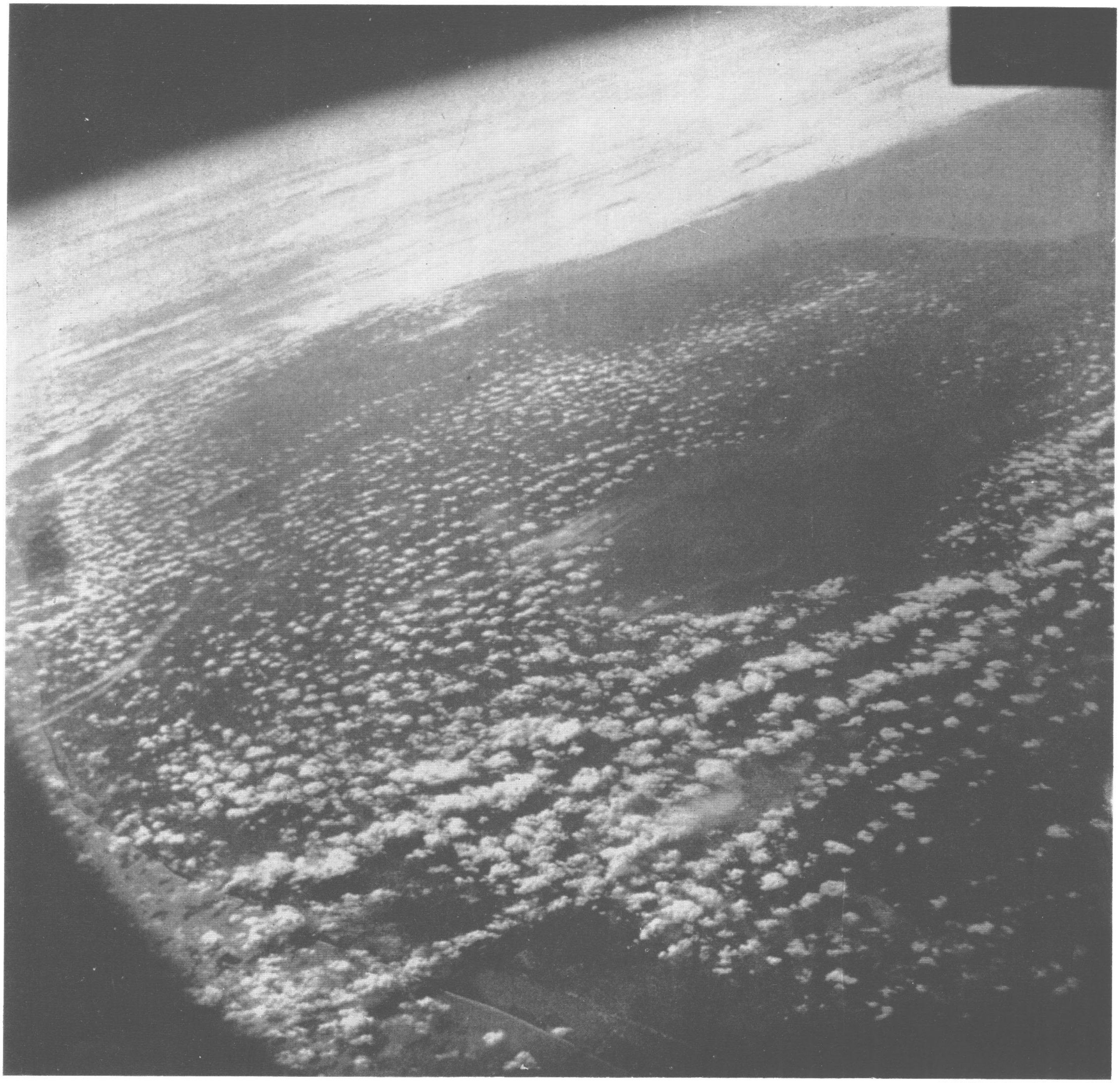

FIGURE 7.—Cloud patterns over southern Florida, January 31, 1961, Mercury-Redstone launch vehicle no. 2.

not unlikely that these two factors were instrumental in producing the cloud bands we watched in Colorado. One of the models of differential friction we had hoped to investigate is this:

Suppose the geostrophic wind is southerly and parallel to the Rocky Mountain Front with rough land to the west, smoother flat land to the east. Friction would slow the wind down over the mountains more than it would over the plains. Therefore, the southerly current over the rough area would be deflected to the west. The greater the braking action of friction, the greater the westward wind deviation. So we have the winds over the mountains deflected westward, the winds over the plains flowing swiftly parallel to the mountain front, and a resultant zone of divergence in between. The effect of this divergence would be to retard the buildup of cumuli in that area. Farther west, beyond the first mountain range, where the land becomes less rugged, there would

FIGURE 8.—Airplane view of clouds over Lake Okeechobee, August 16, 1957, 27,000 ft. (courtesy Dr. R. Cunningham).

be convergence. Here the early formation and rapid development of cumuli into cumulonimbi would be enhanced. This model suggests, then, what we observed: cumulonimbus clouds building up over the mountains in the morning, showers just east of the mountains later in the day. Day after day during the months we spent chasing clouds in northern Colorado and in southern Wyoming, we saw cloud patterns which fit this frictional model for southerly flow. In the satellite picture near Lake Michigan (fig. 3) the clouds over the eastern lake shore, with relatively clear skies to the west of the lake, are what would be expected according to this model of the combined effects of differential friction and heating. Clear skies over the lake would be the result of differential heating. The difference between the east and west shores could be the result of differential friction. Likewise, the smaller cumulus clouds shown in figures 5 through 10 are organized in patterns, apparently by a combination of differential heating with differential friction. High-level pictures, by showing detailed cloud patterns, can help us in deciding just which physical process is at work causing specific cloud arrangements.

FIGURE 9.—Airplane view of southern Florida coast from 27,000 ft., August 16, 1957, showing details of cumulus development (courtesy Dr. R. Cunningham).

High-level pictures should also help us solve another question with which Wexler was concerned: How do horizontal eddies transport atmospheric properties, especially angular momentum and kinetic energy? And how do these eddies exchange such atmospheric properties with the general circulation of the atmosphere? Wexler [15] noted that horizontal eddies probably exist in a full spectrum of sizes in the atmosphere, but that our observational network is too gross to examine mesoscale and smaller eddies. In 1954 when Wexler wrote about this, he thought that such small eddies would act as energy dissipators, transforming kinetic energy to heat. But in 1961 when we went to Colorado, Wexler mentioned that if longitudinally extensive cumulus cloud bands develop over mountains in the presence of instability in the atmosphere, energy from the clouds' latent heat might be systematically transformed into kinetic energy of the upper-level flow in the area and at the same time an organized exchange of momentum would be facilitated. Thus, *organized* mesoscale cloud cells could feasibly con-

Figure 10.—Airplane view of southern Florida coast from 27,000 ft., August 16, 1957, showing cloud streets over land and ocean with clear space in between (courtesy Dr. R. Cunningham).

tribute significantly to the transfer of energy and momentum from surface layers to the upper atmosphere, whereas individual, randomly arranged cells would probably still function as energy dissipators.

To summarize, we have found the clouds in patterns, as Wexler thought we would; but to forecast cloud patterns, their development, and motion, we need to understand more about atmospheric energy sources, sinks, transports, and exchanges, and more about how the upper flow and surface phenomena organize clouds into patterns. For comprehensive cloud and weather prediction, we eagerly await the fruition of Wexler's "World Weather Watch" [11], regular observations from the whole globe at all levels, spot reports from unmanned sea stations, ships, surface land stations, upper-air sondes, radar, and planes, tied together into one cohesive picture by data from satellites.